Expert System Generated Coral Bleaching Alerts for Myrmidon Reef, Great Barrier Reef

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Abstract

An expert system shell was employed at NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) in Miami, Florida, USA, to provide interpretations of combinations of meteorological and oceanographic data collected via a HF radio at the Australian Institute of Marine Science (AIMS) from Myrmidon

Reef, a remote site on the northern Great Barrier Reef, and delivered automatically via FTP over the Internet to AOML. The expert system application, termed the Coral Reef Early Warning System (CREWS), was programmed to identify criteria generally thought to be conducive to coral bleaching. These interpretations were automatically posted to the World-Wide Web and emailed to Great Barrier Reef Marine Park Authority (GBRMPA) and AIMS personnel so they could witness and study bleaching events as they might happen, and so that a model could be developed with greater precision in identifying physical factors conducive to coral bleaching.

Introduction and Background

Coral bleaching may be described as the general whitening of coral tissues due to the release of symbiotic zooxanthellae and/or reduction in photosynthetic pigment concentrations in the zooxanthellae residing within the tissues of the host coral (Glynn 1993). Bleaching can be a generalized stress response to harsh environmental conditions such as high sea temperature or abnormal salinity, bacteriological or viral infection, or for other unknown reasons (Glynn 1993; Brown 1996; Kushmaro et al 1997). In most reported incidences of mass coral bleaching, however, locally high sea temperature is in evidence and appears to be the chief environmental stressor (Brown & Ogden 1993), whether those temperatures may be considered "abnormal" or not (see, for example, Atwood et al 1992). One other event that is thought to favor bleaching, in the presence of high sea temperatures, is the presence of low wind speed, as this is thought to favor localized heating and a greater penetration of solar radiation (Glynn 1993; Causey 1988; Jaap 1978, 1988; Lang 1988).

The Great Barrier Reef (GBR) has seen repeated coral bleaching in recent years (Jones et al 1997). Bleaching events of varying intensity occurred on the GBR in early 1980, 1982, 1987, 1992 and 1994 (Oliver 1985; Hoegh-Gldberg et al 1997; Oliver and

Berkelmans, unpublished data); however, the GBR experienced its most intensive and extensive coral bleaching event on record in early 1998. Mild bleaching commenced in late January and intensified by late February/early March 1998. Because of the importance of the GBR to the economy of Australia, it is desirable to understand the nature of coral bleaching and what factors predict its onset.

The large extent of the GBR, which is comprised of over 2500 individual reefs along a stretch of 2400 km, makes monitoring its physical environment difficult at best. The Australian Institute of Marine Science has a very ambitious program of monitoring physical, chemical and biological features of the GBR (e.g., Sweatman 1997), but one aspect of this program was thought to be of particular interest in correlating physical environmental features to coral bleaching. The AIMS Weather Station Network, comprised of instruments at Myrmidon Reef, Davies Reef and Hardy Reef, present a particular advantage in that they relay near real-time sea temperature, wind and light data, all of which are thought to play a possible role in coral bleaching. A system which could monitor these data automatically, look for matching data patterns that are thought to be conducive to coral bleaching, then produce an alert, would enable researchers to travel to the site of coral bleaching and study the developing phenomenon first hand, rather than after the fact.

Expert systems, or knowledge-based systems, are a branch of artificial intelligence. Artificial intelligence is the capability of a device such as a computer to perform tasks that would be considered intelligent if they were performed by a human (Mockler & Dologite 1992). An expert system is a computer program that attempts to replicate the reasoning processes of experts and can make decisions and recommendations, or perform tasks, based on user input. Knowledge engineers construct expert systems in cooperation with problem domain experts so that the expert's knowledge is available when the expert might not be, and so that the knowledge can be available at all times and in many places, as necessary. Expert systems derive their input for decision making from prompts at the user interface, or from data files stored on the computer, as in the presently described system. The knowledge base upon which the input is matched is generally represented by a series of IF/THEN statements, called production rules, which are written with the domain expert to approximate the expert's reasoning. The degree of belief the expert has in her conclusion may be represented as a confidence factor (CF) in the expert system. For instance, the expert may feel that the conclusion based upon the input has a 95% probability of being correct, so the CF would equal 95. Conclusions may also be represented in fuzzy terms such as "possibly," "probably," or "almost certainly."

The automated methodology we describe here is a data-driven expert system which reviews data collected from Myrmidon Reef and produces alerts when conditions are thought to be conducive to coral bleaching. This expert system is an extension of the Coral Reef Early Warning System (CREWS) originally implemented for Sombrero Key in the Florida Keys, USA (Hendee 1998a, 1998b). The GBR implementation of CREWS is designed to allow researchers to model and further understand the coral bleaching phenomenon, and also to give the GBRMPA managers and AIMS researchers some immediate feedback on one facet of the status or condition of the GBR. An additional benefit is that it automatically alerts researchers so that they may travel to the site for further study, and provide feedback to the knowledge engineer for further fine-tuning of the system (e.g., whether or not bleaching is beginning to occur or not). CREWS screens near real-time incoming wind speed, sea temperature and Photosynthetically Active Radiation (PAR) data (among other types of data) to determine if conditions are optimal for abiotic-induced coral bleaching at Myrmidon Reef, based on a working notion, gleaned from previous research (Berkelmans and Willis 1999) that sustained temperatures over 29.5^{o}C, possibly together with low winds and/or increased solar irradiance, may represent optimal conditions to induce abiotic coral bleaching.

Methods

The basic structure of the expert system was described in Hendee (1998a). The production rules were drawn from previously published data on coral bleaching (Berkelmans and Willis 1999) and from discussions in the literature, as cited above and below. It should be noted, however, that there is still controversy in the literature as to exactly what physical conditions are responsible for isolated instances of coral bleaching (for reviews, see Brown 1996 and Glynn 1993), but generally coral bleaching experts agree that high sea temperature is a major contributing or coincident factor in *mass* coral bleaching episodes.

CREWS excepts as input wind speed, PAR and sea temperature derived from instruments at the station. Thus, depending on how high the sea temperature was, in combination with low winds and/or high PAR, or how high the sea temperature was without low winds, conditions conducive to a coral bleaching event were described in fuzzy terms through automated "alerts," broadcast as email messages and via the World-Wide Web early each morning, as one of the following:

Conditions extremely favorable for bleaching
Conditions very favorable for bleaching
Conditions favorable for bleaching
Conditions probably favorable for bleaching
Conditions possibly favorable for bleaching

If a combination of parameters was considered favorable, and that combination occurred all day, then the combination was considered more favorable (e.g., "very favorable"), rather than if the combination occurred only during one period of the day (e.g., during the afternoon). The system was configured so that alerts were only kept for the previous seven days' worth of alerts, so that if no new production rules were triggered for a whole week, the alerts would no longer be sent after a week's time. At the end of each alert, the number of production rules triggered was calculated and presented.

In a test of the system, a series of scripts were set up to process and review previously collected and archived February, 1998 data, two days' worth at a time, as though the system were being implemented once a day through February in near real-time. This allowed refinement and troubleshooting of the system, which was then put on-line in time for the possible anticipated "bleaching season" during January and February, 1999. Coral bleaching occurred at Myrmidon Reef during February, 1998, so the output of the expert system could be reviewed against the approximate time of bleaching.

At Myrmidon Reef, data are acquired on the hour, every hour, then automatically transmitted at one time every day to a receiving station located at AIMS. Starting in January, 1999, at the same time everyday, a UNIX cron job at AIMS reformatted selected data and sent them via FTP to a workstation located at AOML. A series of UNIX cron jobs at AOML implemented CREWS screening of the data shortly after the scheduled arrival of the data, then, if any alerts were produced, they were emailed to selected coral researchers and posted to a Web site on the AOML workstation. If alerts were not produced, and continued to not be produced for a week's time, the accumulated list of alerts was gradually diminished and finally, at the end of the week, alerts were no longer sent via email or posted to the Web. Alerts that were produced were also archived with unique file names corresponding to the date and time of data collection, and made accessible via the Web. Thus, researchers were notified as soon as conditions conducive to coral bleaching were met, and continued to be notified up to a week after the conditions continued to be met, and the data could be retrieved retrospectively via the Web site.

To verify whether coral bleaching had occurred after the alerts began to be posted, visits were made every two weeks to

Myrmidon Reef during anticipated bleaching to determine the extent of coral bleaching, if any.

Results

AIMS personnel conducted a survey of Myrmidon Reef for signs of bleaching on February 27, 1998. Mild bleaching was reported to be occurring at that time. Another survey, conducted near Myrmidon, showed mild bleaching of *Stylophora pistillata*, *Acropora* (several species), *Seriatopora hystrix* and *Pocillopora damicornis* on February 9, 1998 (Berkelmans, unpublished data). The output of CREWS (Fig. 1) for February 17, 1998, would indicate that the week prior to then, but especially on February 17, conditions were conducive to coral bleaching. Thus, there appears to be very close correlation between the time of actual coral bleaching at Myrmidon Reef, and the hypothesized time of coral bleaching in the test trial of the expert system for the 1998 data.

On the very day of the near real-time implementation of CREWS, January 12, 1999, a coral bleaching alert was produced (Fig. 2). At the time of this writing, however, we have not yet had time to travel to Myrmidon Reef to determine the extent, if any, of coral bleaching.

Discussion

The heuristic for coral bleaching used in the current study, drawn from experimental data (Berkelmans and Willis 1999), states that temperatures over 29.5^{o}C must occur for a whole day before coral bleaching will begin to occur. For the 1998 test implementation of CREWS, the fact that bleaching occurred around February 17, 1998, would tend to support the utility of CREWS in alerting researchers that conditions were conducive to coral bleaching on or about that day. However, coral bleaching is a complex phenomenon, and it is difficult to tell whether high temperature only, or high temperature combined with high PAR, and/or low winds were contributing factors. The effect of ultraviolet radiation (UV) may play an important role in the bleaching response. Jaap (1978) discussed the apparent contribution of low tides and low winds in more rapid solar heating to induce coral bleaching at Middle Sambo Reef in the southern part of the Florida Keys, Florida, USA. However, in light of the work of Lessor et al (1990), and of Gleason & Wellington (1993), who presented convincing evidence of the effect of UV in inducing coral bleaching in *Montastrea annularis* within three weeks, irrespective of water temperature, it may be that the effect of low tides is more a result of greater penetration of UV than of solar heating. Also, low winds result in greater water clarity, due to the reduced effect of wave diffraction of light; hence, a greater penetration of UV.

Only a comparison with non-bleaching years (e.g., 1996) at Myrmidon Reef--a goal for a follow-up study--will yield further insight.

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 Coral Bleaching Alert for 02/17/1998 ~~~~

Rule-T1-ad (24)
Conditions possibly favorable for bleaching all-day on
02/17/1998, because sea temperature was very high (about
29.9).


Rule-TWP1 (24)
Conditions favorable for bleaching on 02/16/1998, because
in situ sea temperature was very high (about 29.7) during
mid-day, wind speed was very low (about 2.8), during mid-
day,  and PAR was high (about 1838) during mid-day.


Rule-TW5 (12)
Conditions possibly favorable for bleaching afternoon on
02/16/1998  because sea temperature was very high (about
30.1), and wind speed was very low (about 5.9) during
afternoon (PAR not considered).


Rule-TWP2 (24)
Conditions favorable for bleaching on 02/15/1998, because
in situ sea temperature was very high (about 29.9) during
mid-day, and PAR was high (about 1663) during mid-day.

[ etc. ]

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High temperature only points:                            24
High temperature, low wind points:                       36
High temperature, low wind, low tide points:              0
High temperature, low wind, high PAR points:            120
High temperature, high PAR points:                       24
High temperature, low wind, high PAR, low tide points:   0

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Total points triggered:                       204
Number of rules triggered:                    10
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Figure 1. Abbreviated output of CREWS for Myrmidon Reef for February 17, 1998 data.

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~~~~ Coral Bleaching Alert for 01/12/1999 ~~~~


Rule-TWP1 (24)
Conditions favorable for bleaching on 01/12/1999, because
in situ sea temperature was very high (about 29.9) during
mid-day, wind speed was very low (about 5.7), during mid-
day, and PAR was high (about 1905) during mid-day.


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High temperature only points:                        0
High temperature, low wind points:                   0
High temperature, low wind, low tide points:         0
High temperature, low wind, high PAR points:         24
High temperature, high PAR points:                   0
High temperature, low wind, high PAR, low tide points: 0

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Total points triggered:                    24
Number of rules triggered:                 1
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Figure 2. CREWS report for Myrmidon Reef on January 12, 1999.